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Recovery of nitrogen fertiliser by drill-sown rice crops using best management practice: a ^{15}N-labelled urea study

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ABSTRACT

Context. Optimising nitrogen (N) management strategies for drill-sown rice crops is essential for minimising input costs for growers and reducing the environmental impact of rice production. **Aims.** The study aimed to determine the recovery of fertiliser-N in drill-sown Australian rice crops, following current N fertiliser recommendations where two-thirds of the N is applied at sowing (pre-flood) and one-third at panicle initiation. **Methods.** ^{15}N-labelled urea was used to quantify N recovery by field-grown rice crops on a Sodosol and a Vertosol, and to determine the contributions of fertiliser-N applied pre-flood vs that applied at panicle initiation to total N fertiliser recovery on the Vertosol. **Results.** Recovery of ^{15}N fertiliser in grain + straw was ~50% of applied N on both soils, with a further 20% recovered from roots and soil to a depth of 30 cm. Recovery of N fertiliser applied at panicle initiation (59%) was significantly higher than of N fertiliser applied pre-flood (43%), likely due to the presence of actively growing roots and higher plant N demand. Crops that received N fertiliser took up more native soil N than unfertilised crops on the Vertosol; hence, apparent fertiliser N recoveries were 10–15% higher than N fertiliser recovery determined using ^{15}N-labelled urea. **Conclusions.** The recovery of 50% of fertiliser-N in aboveground plant material indicates that N fertiliser use efficiency in drill-sown rice is similar to that of dryland cereal crops in Australia when best management practice guidelines for N fertiliser use are followed.

Keywords: direct seeding, fertiliser efficiency, isotope, nitrogen recovery, nitrogen use efficiency, temperate rice crops, water savings, water use efficiency.

Introduction

Over 70% of the world's rice (*Oryza sativa* L.) is grown under flooded (paddy) conditions, making the global rice industry a large user of irrigation water. In recent years there has been a push to reduce water usage in rice production owing to costs and competing demands for water (Rejesus *et al.* 2011). In turn, this has led to adoption of management strategies including 'alternate wetting and drying' (AWD), which integrates an aerobic growth phase in the crop cycle to reduce water use (Carrijo *et al.* 2017). In the Australian rice industry, AWD strategies involving aerobic growth between panicle initiation (PI) and anthesis are not generally feasible because deep water (>25 cm) is needed to protect the crop from cold temperature stress, which can cause severe yield losses (Williams and Angus 1994). As such, water savings in Australian rice crops are typically achieved by drill sowing crops instead of sowing into flooded fields, and growing the crop aerobically until the 3–4-leaf stage ('drill sowing') or until 2–3 weeks before PI (delayed permanent water, DPW) (Dunn *et al.* 2014). Adoption of DPW has been shown to increase water productivity by 17% compared with standard drill sowing practices under Australian conditions (Dunn and Gaydon 2011).

Nitrogen (N) fertiliser management in drill-sown or DPW crops is also critical because broadcasting N fertiliser into floodwater is highly inefficient, with crops recovering as little as 28% of applied fertiliser-N (Humphreys *et al.* 1987). Higher N fertiliser recoveries in drill-sown crops are achieved when N is applied immediately prior to permanent flooding (Humphreys et al. 1987; Norman et al. 2009). Broadcasting urea onto the soil immediately prior to permanent flooding is therefore currently recommended for both drill-sown and DPW crops in Australia (Dunn et al. 2014, 2016). Using this N application method, apparent N recoveries (i.e. the amount of N accumulated in shoots of an N-fertilised crop minus N accumulated in shoots of an unfertilised crop, divided by the amount of N fertiliser applied) in drill-sown crops range from ~50% to 70% (Dillon et al. 2012; Dunn et al. 2014).

One issue with apparent N fertiliser recovery estimates is the inherent assumption that the N-fertilised crop takes up the same amount of native soil N as the unfertilised crop, and thus the difference between their shoot N accumulation values represents the amount of fertiliser-N taken up by the fertilised crop. However, this assumption is not always valid because the addition of N fertiliser may stimulate greater crop growth and root exploration to take up more native soil N, or can lead to soil N priming, where more native soil N is mineralised (Kuzyakov et al. 2000). Either or both of these processes can lead to N-fertilised plants acquiring more N from the native soil N pool than unfertilised plants. The use of ^{15}N-labelled fertiliser can overcome this obstacle to accurate estimation by directly measuring the uptake of N from the labelled N fertiliser source.

In a study on a Sodosol (Australian Soil Classification; Isbell 1996) in south-eastern Australia, there was no difference in crop recovery of N from ^{15}N-urea fertiliser between crops grown under full flood or DPW watering regimes, with ~27% of fertiliser-N recovered in grain and straw at maturity under both regimes (Rose et al. 2016). However, all N fertiliser was supplied at sowing (for full flood) or pre-flood (for DPW) in that study, whereas splitting N fertiliser applications between pre-flood and PI is currently recommended for drill-sown rice crops (Dunn et al. 2014, 2016). Therefore, we wished to know whether there is a difference in crop recovery of N from ^{15}N-urea fertiliser depending on when the fertiliser is applied. The present study investigated the recovery of ^{15}N-urea by drill-sown rice crops grown on a Sodosol when all N was applied at immediately prior to permanent water (PW), or with an extra application at PI. We further investigated N fertiliser recovery on a Vertosol where the fertiliser was applied in total at PW or as a 2:1 split between PW and PI, and specifically examined the recovery of N from ^{15}N-labelled urea applied at PW versus PI.

Materials and methods

Field sites and experimental layout

Two field trials were conducted in the Murrumbidgee Irrigation Area of southern New South Wales, Australia, in the 2016–17 rice growing season. One field trial was established on a Sodosol at Yanco Agricultural Institute (YAI) (−34.613181, 146.419479) and another was established on a Vertosol at Leeton Field Station (LFS) (−34.605339, 146.362144). Selected soil chemical properties of the 0–150 mm layer of the soils are presented in Table 1.

At both trial sites, microplots were established in rice fields in an area that did not receive any N fertiliser, by inserting 300-mm-diameter metal rings to a depth of 150 mm in the soil after the first 'flush' irrigation. Details of the rice crop management and timing of permanent water and N applications for each trial site are given in Table 2. For PW applications, ^{15}N-labelled urea (5.1 atom % ^{15}N) was applied by hand to each microplot in appropriate treatments, and for application at PI, by hand directly into floodwater within the rings.

At LFS, five treatments were established that differed with regard to timing of N application (applied in full at PW, or split 2:1 between PW and PI) and, for split applications, whether the N fertiliser was unlabelled or ^{15}N-labelled urea. The five treatments (kg N ha^{-1}, application PW/PI) were: (i) nil/nil (i.e. control); (ii) 180 kg as ^{15}N-labelled urea/nil (180^{15}N/0N); (iii) 120 kg/60 kg, both as ^{15}N-labelled urea (120^{15}N/60^{15}N); (iv) 120 kg as unlabelled urea/60 kg as ^{15}N-labelled urea (120N/60^{15}N); and (v) 120 kg as ^{15}N-labelled urea/60 kg as unlabelled urea (120^{15}N/60N). Three replicate

Table 1. Selected properties of 0–150 mm layer of soils in experimental fields at Leeton Field Station and Yanco Agricultural Institute.

Property	Leeton Field Station	Yanco Agricultural Institute
Organic carbon (%)	1.4	1.5
pH (1:5 H_2O)	6.0	4.3
Electrical conductivity (dS m^{-1})	0.07	0.04
Colwell phosphorus (mg kg^{-1})	73	140
Effective cation exchange capacity (cmol(+) kg^{-1})	26.2	6.8
Base cations (cmol(+) kg^{-1})		
Calcium	17	3.4
Magnesium	7.4	1.6
Potassium	1.7	1.0
Sodium	0.2	0.1
Aluminium	<0.1	0.8
DTPA-extractable micronutrients (mg kg^{-1})		
Zinc	1.4	2.4
Manganese	11	18
Iron	110	410
Copper	6.3	3.1

Samples were tested at Incitec Pivot laboratories (Werribee, Vic., Australia) using methods from Rayment and Lyons (2011).

Table 2. Trial management calendar for ^{15}N trials on rice grown at Yanco Agricultural Institute and Leeton Field Station in 2016–17.

Trial management	Yanco Agricultural Institute	Leeton Field Station
Land preparation		
Discing	15 Sept. 2016	20 Sept. 2016
Power harrowing and levelling	10 Oct. 2016	09 Oct. 2016
Rice sown		
Date	28 Oct. 2016	19 Oct. 2016
Cultivar	Reiziq	Reiziq
Seeding rate	150 kg ha^{-1}	150 kg ha^{-1}
Row spacing	18 cm	18 cm
Fertiliser applied		
Nitrogen at permanent water	02 Dec. 2016	02 Dec. 2016
Nitrogen at panicle initiation	10 Jan. 2017	10 Jan. 2017
Herbicides		
Clomazone (480 g L^{-1}) @600 mL ha^{-1}	07 Nov. 2016	28 Oct. 2016
Propanil (480 g L^{-1}) @8 L ha^{-1}	01 Dec. 2016	01 Dec. 2016
Water		
First flush	31 Oct. 2016	21 Oct. 2016
Permanent water	02 Dec. 2016	02 Dec. 2016
Panicle initiation	10 Jan. 2017	10 Jan. 2017
Harvest	19 Apr. 2017	19 Apr. 2017

microplot rings per treatment were positioned in a 3 × 5 layout with 5 m between rings in the unfertilised area of the field, with treatments positioned randomly.

At YAI, three treatments (kg N ha^{-1}, application IPPW/PI) were established: (*i*) nil/nil (control); (*ii*) 120 kg as ^{15}N-labelled urea/nil (120^{15}N/0N); and (*iii*) 120 kg/60 kg, both as ^{15}N-labelled urea (120^{15}N/60^{15}N). Three replicate microplot rings per treatment were positioned in a 3 × 3 layout with 5 m between rings in the unfertilised area of the field, with treatments positioned randomly. Unfortunately, however, the control plots received 60 kg N ha^{-1} as unlabelled urea at PI (0N/60N), and therefore did not represent a nil-N control. A parallel incubation experiment was conducted in the laboratory at YAI to determine whether addition of the unlabelled urea affected soil ^{15}N abundance. The 90-day incubation experiment used unfertilised soil adjacent to the YAI trial, with soil samples (20 g) placed in 200-mL containers and incubated in the dark at 25°C. Addition of 60, 120 or 180 kg N ha^{-1} to soil (on a weight basis, calculated using soil bulk density and an assumed urea penetration depth of 100 mm into soil) had no significant effect on the ^{15}N abundance of the soil after 90 days (mean ^{15}N abundance +7.5‰ (±0.09‰)). Plant and soil material from the 0N/60N microplots was thus used as 'nil-N' material for calculations below.

Measurements

At crop maturity, plant height was measured with a ruler before all aboveground material within the rings was harvested by severing shoots at ground level, and grain was manually separated from the straw. Rings were removed by digging away the surrounding soil with a shovel, and the top 300 mm of the soil and roots was retained, comprising the top 150 mm of soil + roots within the inserted ring and the next layer (150–300 mm) of soil + roots below the ring. The two layers of soil + roots were kept separate. Roots were then separated from soil by dry sieving to remove the bulk of soil, followed by hand-washing through multiple sieves to clean the roots. Root material from the two soil layers was combined for each plot, whereas soil material from the two layers was kept separate. All plant tissue and soil material was then dried for 3 days at 60°C. Plant material was then weighed before all plant and soil material was finely ground for analysis of total N concentration by using a TruMAC CNS analyser (LECO, MI, USA) and quantification of N isotope ratios via a Thermo Delta V Plus isotope ratio mass spectrometer (Thermo Fisher Scientific, Waltham, MA, USA) following combustion on a Thermo Flash EA 1112 elemental analyser (Thermo Fisher Scientific). For total N concentrations, subsamples (200 mg) were combusted for all material, whereas for N isotope ratios, 1 mg was combusted for plant material and 4 mg was combusted for soil material.

Calculations

Aboveground biomass was calculated by summing grain and straw biomass, and total plant biomass was calculated by summing root, straw and grain biomass. Harvest index was calculated by dividing grain biomass by aboveground biomass. The N content of root, straw and grain tissues was calculated by multiplying the biomass by the respective tissue N concentration. Plant aboveground N content was calculated by summing grain N content and straw N content. Total plant N content was calculated by summing root, straw and grain N contents.

For each soil layer (0–150 and 150–300 mm), the N content (kg N ha^{-1}) was calculated by multiplying the weight of the layer per ha by the %N concentration in the layer. The weight of soil in each layer (kg ha^{-1}) within the microplot was calculated by using the bulk density of the layer.

All ^{15}N data were expressed as the atom % excess, corrected for background abundance (0.36765%). The percentage of N derived from fertiliser (%Ndff; derived from the ^{15}N-labelled urea portion of applied N) in plant and soil samples was calculated using the equation:

$$\%\text{Ndff} = 100 \times (a - b)/(c - b) \tag{1}$$

where a is the atom % ^{15}N in the treatment plant or soil sample; b is the % ^{15}N in the unfertilised (control) plant or soil sample; and c is the atom % ^{15}N in the fertiliser (5.1%). Note that for the YAI trial, the b value was obtained from plant or soil that had received 60 kg N as unlabelled urea at PI.

The percentage of applied ^{15}N fertiliser recovered in each plant tissue and soil layer (%NFR) was calculated as:

$$\%NFR = 100 \times (\%Ndff \times d)/e \quad (2)$$

where %Ndff is as previously defined, d is the kg N ha^{-1} in plant tissue or soil layer, and e is the amount of N fertiliser applied (kg N ha^{-1}).

The percentage of fertiliser-N recovered in aboveground plant material was calculated by summing the per cent recovery in grain and straw tissue, and the per cent recovery in plants was calculated by summing the per cent recovery of root, straw and grain tissue. Finally, the total fertiliser N recovery in the system was calculated by summing the per cent recovery in plants and per cent recovery in each soil layer.

Apparent N fertiliser recovery for each of the N-fertilised treatments at LFS was calculated by subtracting the aboveground N content from the nil-N plots from the aboveground N content of treated plots, and dividing by the amount of N fertiliser applied (in kg N ha^{-1}) and expressing as a percentage. No apparent N fertiliser recovery could be calculated at YAI because nil-N plots received 60 kg N ha^{-1} as unlabelled urea at PI.

Statistical analyses

For each trial site, plant biomass, grain yield, harvest index and grain N data, and %Ndff and %NFR data were analysed by one-way analysis of variance fitting N fertiliser treatment in GenStat Release 16.1 (VSN International, Hemel Hempstead, UK), using a probability level of 0.05. Significance of differences between treatment means at each trial site was tested by using Duncan's multiple range test at $P = 0.05$.

Results

Biomass and grain yields

Grain yield at YAI increased significantly ($P < 0.05$), by >5 t ha^{-1}, in response to N fertiliser application at PW (120^{15}N/0N) compared with application only at PI (0N/60N), with a further significant increase of 2 t ha^{-1} when an additional 60 kg N ha^{-1} was applied at PI (120^{15}N/60^{15}N) (Table 3). This trend was also reflected in total aboveground biomass and total biomass (Table 3). At LFS, grain yield in the nil N control (5.4 t ha^{-1}) was significantly lower than in all of the treatments with N applied, where yields were >13 t ha^{-1} and not significantly different from each other.

Harvest index and grain N

The harvest index did not differ among treatments at either site, with a mean of ~0.5 in all treatments at both field sites. Similarly, grain N percentage did not differ between treatments at either site, with a mean of ~1% for all treatments at both sites (Table 3).

Plant N accumulation and percentage of N derived from fertiliser in plant tissues

At YAI, the 120^{15}N/60^{15}N treatment resulted in significantly higher %Ndff than the 120^{15}N/0N treatment for grains (39.5% vs 27.1%) and straw (33.2% vs 23.5%), resulting in

Table 3. Biomass yields and N accumulation under varying N fertiliser regimes at Yanco Agricultural Institute and Leeton Field Station in the 2016–17 rice season.

Site and N fertiliser treatment	Plant height (cm)	Grain yield (t ha^{-1})	Straw biomass (t ha^{-1})	Root biomass (t ha^{-1})	Aboveground biomass (t ha^{-1})	Total biomass (t ha^{-1})	Harvest index	Grain N (%)
Yanco Agricultural Institute								
0N/60N	73.3a	10.3a	11.4a	17.0a	21.7a	38.7a	0.47a	1.09a
120^{15}N/0N	79.0a	15.4b	15.0b	28.0a	30.4b	58.3b	0.51a	1.02a
120^{15}N/60^{15}N	78.0a	17.6c	16.2c	25.6a	33.9b	59.5b	0.52a	1.02a
Leeton Field Station								
0N/0N	61.0a	5.4a	5.1a	6.2a	10.5a	16.7a	0.52a	1.04a
180^{15}N/0N	73.7b	13.6b	15.5b	20.1b	29.0b	49.1b	0.47a	0.97a
120^{15}N/60^{15}N	74.0b	14.3b	14.3b	18.8b	28.6b	47.4b	0.50a	1.06a
120N/60^{15}N	73.0b	14.6b	15.3b	21.3b	29.9b	51.2b	0.49a	1.00a
120^{15}N/60N	71.3b	14.8b	14.3b	20.2b	29.1b	49.3b	0.51a	1.04a

Within a column, for a given field site, means followed by the same letter are not significantly different at $P = 0.05$. Values for each N fertiliser treatment indicate the amount of N per ha (application immediately prior to permanent water/panicle initiation); ^{15}N indicates application of N as ^{15}N-labelled urea, and N indicates application as unlabelled urea.

Table 4. Percentage of N derived from fertiliser (%Ndff; derived from the ^{15}N-labelled urea portion of applied N) in plant tissues and whole plants at Yanco Agricultural Institute and Leeton Field Station.

Site and N fertiliser treatment	$\%Ndff_{grain}$	$\%Ndff_{straw}$	$\%Ndff_{root}$	$\%Ndff_{aboveground}$	$\%Ndff_{plant}$
Yanco Agricultural Institute					
$120^{15}N/0N$	27.1a	23.5a	10.1a	26.0a	22.4a
$120^{15}N/60^{15}N$	39.5b	33.2b	8.9a	37.6b	30.8b
Leeton Field Station					
$180^{15}N/0N$	45.7c	37.2c	17.8c	43.0c	37.3c
$120^{15}N/60^{15}N$	45.6c	38.0c	18.1c	43.5c	38.7c
$120N/60^{15}N$	18.4a	13.2a	5.54a	16.8a	14.4a
$120^{15}N/60N$	25.1b	23.5b	10.7b	24.6b	22.0b

Within a column, for a given field site, means followed by the same letter are not significantly different at $P = 0.05$. Values for each N fertiliser treatment indicate the amount of N per ha (application immediately prior to permanent water/panicle initiation); ^{15}N indicates application of N as ^{15}N-labelled urea, and N indicates application as unlabelled urea.

higher overall %Ndff in aboveground plant material (37.6% vs 26.0%) and all plant material (30.8% vs 22.4%) (Table 4). This was reflected in a significantly greater amount of aboveground plant N derived from ^{15}N-labelled fertiliser in the $120^{15}N/60^{15}N$ treatment than the $120^{15}N/0N$ treatment (93 vs 58 kg N ha^{-1}) (Fig. 1*a*). Ultimately, uptake of N from soil and unlabelled N fertiliser did not differ among treatments (mean of ~163 kg N ha^{-1}). Aboveground N accumulation increased significantly with increasing N application from 60 to 180 kg N ha^{-1} (Fig. 1*a*), which mirrored the trend in grain yields.

At LFS, %Ndff in whole plants was in the order $180^{15}N/0N = 120^{15}N/60^{15}N > 120^{15}N/60N > 120N/60^{15}N$, and this same trend was observed for all tissues and aboveground plant material (Table 4). It is noteworthy that the sum of $\%Ndff_{plant}$ of the treatments $120^{15}N/60N$ (22.0%) and $120N/60^{15}N$ (14.4%) of 36.4% was similar to the treatments where 180 kg ^{15}N ha^{-1} was applied in total (37.3% for $180^{15}N/0N$ and 38.7% for $120^{15}N/60^{15}N$). Ultimately, ~43% of aboveground N was derived from ^{15}N-labelled fertiliser in treatment $180^{15}N/0N$, where all N was applied as ^{15}N labelled fertiliser at PW, compared with 25% and 17% in treatments $120^{15}N/60N$ and $120N/60^{15}N$, where ^{15}N-labelled fertiliser was applied at PW and PI, respectively (Table 4). This was reflected in the proportion of aboveground N content derived from ^{15}N-labelled fertiliser, where 83 and 90 kg N ha^{-1} was derived from ^{15}N fertiliser in the $180^{15}N/0N$ and $120^{15}N/60^{15}N$ treatments, respectively, compared with 52 kg N ha^{-1} in the $120^{15}N/60N$ treatment and 35 kg N ha^{-1} in the $120N/60^{15}N$ treatment (Fig. 1*b*). Notably, 81 kg N ha^{-1} was taken up from the soil in the nil-N control treatment, but where 180 kg N ha^{-1} was added as ^{15}N-labelled urea (i.e. $180^{15}N/0N$ and $120^{15}N/60^{15}N$), native soil N uptake was significantly higher at ~115 kg N ha^{-1} (Fig. 1*b*). The differences in non-^{15}N-labelled urea uptake between the $180^{15}N/0N$ and $120^{15}N/60^{15}N$ treatments and the $120^{15}N/60N$ and $120N/60^{15}N$ treatments are attributed to uptake of N from unlabelled urea as opposed to differences in native soil N uptake, because the total aboveground N content did not differ between treatments where a total of 180 kg N ha^{-1} was added (Fig. 1*b*).

^{15}N fertiliser recovery in plants and soil

At YAI there was no significant difference in ^{15}N recovery in plant or soil material between the $120^{15}N/0N$ and $120^{15}N/60^{15}N$ treatments (Table 5). Approximately 50% of applied N was recovered in aboveground plant material, with a total N fertiliser recovery (i.e. all plant and soil material) of ~70%.

At LFS, a significantly higher proportion of the ^{15}N was recovered in aboveground plant material when applied only at PI ($120/60^{15}N$, 62.3%) than when ^{15}N was applied only at PW ($120^{15}N/60N$, 47.3%; $180^{15}N/0N$, 51.9%) (Table 5). This was due to significantly greater ^{15}N recovery in grains (44.8% when ^{15}N was applied only at PI vs 32.2% in $120^{15}N/60N$ and 33.2% in $180^{15}N/0N$), because recovery of ^{15}N in straw and root tissue did not differ significantly among treatments (Table 5). Notably, when ^{15}N was applied at both PW and PI ($120^{15}N/60^{15}N$), the per cent recovery of ^{15}N in grains (38.4%) and whole plants (55.4%) was intermediate to, and not significantly different from, recovery when ^{15}N was applied solely at PI or solely at PW. Despite a higher per cent recovery of ^{15}N in plants when applied solely at PI, there was no significant difference in the total recovery of ^{15}N in the plant–soil system ($\%NFR_{total}$) between any two treatments (mean 73.0%) owing to lower recovery of ^{15}N applied at PI in the soil (9.6% at 0–150 mm and 0.4% at 150–300 mm) (Table 5). Finally, apparent recovery of N fertiliser did not differ among treatments (mean 68.7%) but was substantially higher than the mean aboveground plant ^{15}N recoveries, which ranged from 43.0% in $120^{15}N/60N$ to 58.5% in $120N/60^{15}N$ (Table 5).

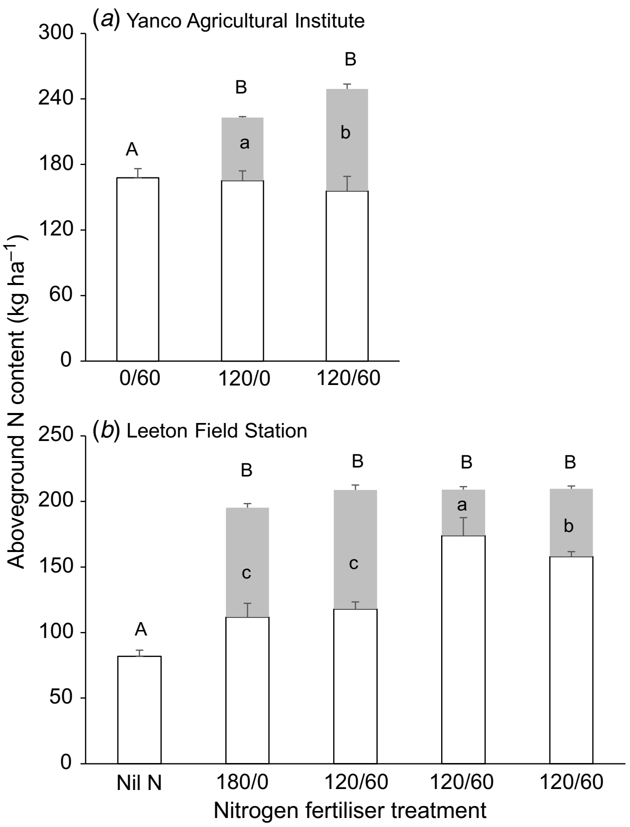

Fig. 1. Impact of N fertiliser treatment on accumulation of N in aboveground plant material in rice crops at (*a*) Yanco Agricultural Institute and (*b*) Leeton Field Station. Grey section indicates crop uptake of N from ^{15}N-labelled urea, white area indicates crop uptake of N from native soil N sources (180^{15}N/0N and 120^{15}N/60^{15}N at Leeton) or from a combination of native soil N and unlabelled urea (all Yanco data and 120^{15}N/60N and 120N/60^{15}N treatments at Leeton). For each site, treatment means with the same upper case letter are not significantly different at $P = 0.05$ for total aboveground N content, and treatment means with the same lower case letter are not significantly different for uptake of N from ^{15}N-labelled urea at $P = 0.05$. Values for each N fertiliser treatment indicate the amount of N per ha (application immediately prior to permanent water/ panicle initiation).

Discussion

Recovery of fertiliser-N by flooded rice crops has traditionally been low (20–40%), owing to a combination of N_2 losses and NH_3 volatilisation losses (Vlek and Byrnes 1986). However, agronomic research over the past three decades has led to optimisation of both the rate and timing of N fertiliser application to minimise N losses and maximise crop yields. In Australia, it is currently recommended that two-thirds of N be applied IPPW in drill-sown crops, with the final third applied at PI (Dunn *et al.* 2016). With a standard N rate of 180 kg ha^{-1} split between IPPW and PI applications, recovery of ^{15}N fertiliser in aboveground tissue (grain and straw) was ~50% of applied N on both the Sodosol (YAI) and Vertosol (LFS), with total N recovery (all plant material and soil recovery to 30 cm depth) of almost 70% (Table 5). Given an average aboveground recovery of ^{15}N fertiliser of 44% (±14%) by dryland crops in Australia (Angus and Grace 2017), our results indicate that high-yielding, drill-sown rice crops can have similar fertiliser-N recoveries to those of dryland crops when optimised N fertiliser management strategies are employed.

The 48.1% recovery of ^{15}N in aboveground tissue when 120 kg N ha^{-1} was applied only IPPW at YAI (120^{15}N/0N) was slightly lower (although not significantly so) than recovery in the 120^{15}N/60^{15}N treatment (51.8%), but substantially greater than the 29% recovery reported by Rose *et al.* (2016) when 120 kg N ha^{-1} was applied pre-flood in a drill-sown crop grown on a similar Sodosol. We suggest the difference in N fertiliser recoveries between the present study and the earlier study was largely due to lower crop yields in the earlier study, where aboveground biomass and grain yields were 19 t and 10 t ha^{-1}, respectively, compared with 30 t and 15 t ha^{-1} in the present study (Table 3). The poorer growth in the study by Rose *et al.* (2016) may have diminished crop N demand and, therefore, crop recovery of fertiliser-N, although differences in rice variety or other soil or seasonal conditions may also have contributed. Similar results have been reported for drill-sown rice crops in southern USA, where ^{15}N fertiliser recovery in grain and straw from split N application (100 kg N ha^{-1} pre-flood + 34 kg N ha^{-1} at PI) was 35% in one season but was 48% in the same field in the subsequent season, when rice biomass production and grain yields were higher (Bollich *et al.* 1994).

Although the overall recovery of ^{15}N fertiliser in straw and grain was ~50% in the 120^{15}N/60^{15}N treatments at both field sites (Table 5), at LFS the recovery and partitioning of ^{15}N applied at IPPW differed from ^{15}N applied at PI. A greater proportion of ^{15}N was recovered by plants when applied solely at PI (58.5% for aboveground material and 62.3% for whole plants) than when applied only at IPPW (43.0% for aboveground material and 47.3% for whole plants). This is consistent with earlier reports that N fertiliser applied at PI is recovered more efficiently by rice crops than N applied pre-flood (Westcott *et al.* 1986; Bacon and Heenan 1987). This greater efficiency of fertiliser-N uptake at PI has generally been attributed to greater plant N demand at this stage than at earlier growth stages (Westcott *et al.* 1986) rather than any specific conditions in the soil at PI that reduce the chance of N loss through denitrification.

Owing to a lower proportion of ^{15}N being recovered in the soil when applied at PI, there was no significant difference in overall system recovery of ^{15}N, presuming that the ^{15}N in the soil would still be present and available for subsequent crops. The higher per cent recovery of ^{15}N in the 120N/60^{15}N treatment was due greater recovery in grain tissue (Table 5),

Table 5. Percentage of N fertiliser recovery (%NFR) from ^{15}N-labelled urea in plant tissue and soil and apparent N fertiliser recovery at Yanco Agricultural Institute and Leeton Field Station.

Site and N fertiliser treatment	% NFR_{grain}	% NFR_{straw}	% NFR_{roots}	% $NFR_{aboveground}$	% NFR_{plant}	% $NFR_{soil\ (0–150)}$	% $NFR_{soil\ (150–300)}$	% NFR_{total}	Apparent recovery (%)
Yanco Agricultural Institute									
120^{15}N/0N	35.4a	12.7a	5.2a	48.1a	53.2a	16.1a	0.8a	70.1a	NA
120^{15}N/60^{15}N	39.1a	12.7a	3.8a	51.8a	55.7a	12.1a	0.6a	68.4a	NA
Leeton Field Station									
180^{15}N/0N	33.2a	13.2a	5.5a	46.4a	51.9a	25.0b	0.9a	77.7a	63.0a
120^{15}N/60^{15}N	38.4ab	12.0a	5.0a	50.4ab	55.4ab	17.5ab	0.3a	73.3a	70.4a
120/60^{15}N	44.8b	13.7a	3.9a	58.5b	62.3b	9.6a	0.4a	72.3a	70.6a
120^{15}N/60N	32.2a	10.9a	4.3a	43.0a	47.3a	20.9b	0.3a	68.5a	71.0a

Within a column, for a given site, means followed by the same letter are not significantly different at $P = 0.05$. Values for N fertiliser treatment indicate the amount of N per ha (application immediately prior to permanent water/panicle initiation); ^{15}N indicates application of N as ^{15}N-labelled urea, and N indicates application as unlabelled urea.

Apparent recovery of N fertiliser in aboveground material was calculated by subtracting the aboveground N content in the nil-N treatment from the aboveground N content of the N fertiliser treatment; NA, not available (no nil-N treatment).

suggesting that N applied at PI was also partitioned among plant tissues differently from N applied at IPPW. This is supported by the fact that 18% of grain N in the 120N/60^{15}N treatment was derived from the 60 kg N ha^{-1} as ^{15}N-labelled fertiliser, whereas only 25% of grain N was derived from ^{15}N-labelled fertiliser when 120 kg ^{15}N ha^{-1} was applied at IPPW (120^{15}N/60N; Table 4). Although the lack of difference in per cent grain N derived from fertiliser between the 180^{15}N/0N and 120^{15}N/60^{15}N treatments appears at odds with this, these numbers are not directly comparable because grain yields differed between these treatments (i.e. lower on average by ~1 t ha^{-1} in the 180^{15}N/0N treatment, although not significant at $P = 0.05$). The lack of a significant yield difference between the N-fertilised treatments also highlights the fact that higher recovery of ^{15}N at PI is not necessarily associated with higher yields, and as noted by Bollich *et al.* (1994), split N applications can actually lead to yield losses when insufficient N is applied earlier in the season. This relationship between crop phenology and N supply is also cultivar dependent (Bollich *et al.* 1994), and emphasises the importance of ongoing agronomic research to optimise N fertiliser rate and timing for new cultivars as they are released from breeding programs.

Apparent N fertiliser recovery in drill-sown crops ranges from 50% to 70% (Dillon *et al.* 2012; Dunn *et al.* 2014); however, experimental comparisons in rice suggest that N fertiliser recoveries derived by using ^{15}N-labelled fertiliser are substantially lower than the apparent N fertiliser recoveries (Humphreys *et al.* 1987). This was observed at LFS in our study, where the mean apparent N fertiliser recovery in the split N treatments (120^{15}N/60^{15}N, 120^{15}N/60N and 120N/60^{15}N) was ~70%, whereas the mean ^{15}N recovery of these three treatments was ~50% (Table 5). This difference is attributed to greater uptake of native soil N where N fertiliser was added, as indicated by additional 30–35 kg ha^{-1} of native soil N accumulated in 180^{15}N/0N and 120^{15}N/60^{15}N treatments (Fig. 1). Whether this was due to greater root exploration or soil N priming, or a combination of both, is not known. Ultimately, the crop N uptake data from LFS also indicated that >50% of crop N uptake in the 180^{15}N/0N and 120^{15}N/60^{15}N treatments was derived from the soil, clearly demonstrating the reliance of flooded rice crops on native soil N sources for much of their N demand (see also Bacon and Heenan 1987; Cassman *et al.* 1998).

Finally, it is acknowledged that the rings used for the microplots in the study were inserted only 150 mm into the soil, and it is possible that some of ^{15}N-labelled urea moved deeper into the soil and out of the sampling area. However, previous ^{15}N studies on flooded rice in Australia (Humphreys *et al.* 1987) and elsewhere (Westcott *et al.* 1986; Bollich *et al.* 1994) have all used similar methodology; therefore, our results are directly comparable to these earlier studies.

Conclusions

The recovery of ~50% of applied N fertiliser in rice plants (grain + straw) suggests that following best management practice for N application in drill-sown rice crops leads to more effective N capture than typically observed in traditional flooded rice crops (20–40%; Vlek and Byrnes 1986). The most effective recovery of N fertiliser occurs when N is applied at PI, likely due to greater root surface area and crop N demand at this time compared with N application at IPPW. Ultimately, the 50% fertiliser-N recovery in straw + grain material demonstrates that N fertiliser use efficiency in drill-sown rice is similar to that of dryland cereal crops in Australia when current best practice guidelines for N fertiliser use are followed.

References

Angus JF, Grace PR (2017) Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. *Soil Research* **55**, 435–450. doi:10.1071/SR16325

Bacon PE, Heenan DP (1987) Nitrogen budgets for intensive rice growing in Southern Australia. In 'Efficiency of nitrogen fertilisers in rice'. (Eds JR Freney, R Wetselaar, ACF Trevitt, JR Simpson) pp. 89–95. (International Rice Research Institute: Los Baños, Philippines)

Bollich PK, Lindau CW, Norman RJ (1994) Management of fertiliser nitrogen in dry-seeded, delayed-flood rice. *Australian Journal of Experimental Agriculture* **34**, 1007–1012. doi:10.1071/EA9941007

Carrijo DR, Lundy ME, Linquist BA (2017) Rice yields and water use under alternate wetting and drying irrigation: a meta-analysis. *Field Crops Research* **203**, 173–180. doi:10.1016/j.fcr.2016.12.002

Cassman KG, Peng S, Olk DC, Ladha JK, Reichardt W, Dobermann A, Singh U (1998) Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Research* **56**, 7–39. doi:10.1016/S0378-4290(97)00140-8

Dillon KA, Walker TW, Harrell DL, Krutz LJ, Varco JJ, Koger CH, Cox MS (2012) Nitrogen sources and timing effects on nitrogen loss and uptake in delayed flood rice. *Agronomy Journal* **104**, 466–472. doi:10.2134/agronj2011.0336

Dunn BW, Gaydon DS (2011) Rice growth, yield and water productivity responses to irrigation scheduling prior to the delayed application of continuous flooding in south-east Australia. *Agricultural Water Management* **98**, 1799–1807. doi:10.1016/j.agwat.2011.07.004

Dunn BW, Dunn TS, Beecher HG (2014) Nitrogen timing and rate effects on growth and grain yield of delayed permanent-water rice in south-eastern Australia. *Crop & Pasture Science* **65**, 878–887. doi:10.1071/CP13412

Dunn BW, Dunn TS, Orchard BA (2016) Nitrogen rate and timing effects on growth and yield of drill-sown rice. *Crop & Pasture Science* **67**, 1149–1157. doi:10.1071/CP16331

Humphreys E, Chalk PM, Muirhead WA, Melhuish FM, White RJG (1987) Effects of time of urea application on combine-sown Calrose rice in south-east Australia. III. Fertiliser nitrogen recovery, efficiency of fertilisation and soil nitrogen supply. *Australian Journal of Agricultural Research* **38**, 129–138. doi:10.1071/AR9870129

Isbell RF (1996) 'The Australian Soil Classification.' (CSIRO Publishing: Melbourne, Vic., Australia)

Kuzyakov Y, Friedel JK, Stahr K (2000) Review of mechanisms and quantification of priming effects. *Soil Biology and Biochemistry* **32**, 1485–1498. doi:10.1016/S0038-0717(00)00084-5

Norman RJ, Wilson CE Jr, Slaton NA, Griggs BR, Bushong JT, Gbur EE (2009) Nitrogen fertilizer sources and timing before flooding dry-seeded, delayed-flood rice. *Soil Science Society of America Journal* **73**, 2184–2190. doi:10.2136/sssaj2008.0309

Rayment GE, Lyons DJ (2011) 'Soil chemical methods: Australasia.' (CSIRO Publishing: Melbourne, Vic., Australia)

Rejesus RM, Palis FG, Rodriguez DGP, Lampayan RM, Bouman BAM (2011) Impact of the alternate wetting and drying (AWD) water-saving irrigation technique: evidence from rice producers in the Philippines. *Food Policy* **36**, 280–288. doi:10.1016/j.foodpol.2010.11.026

Rose TJ, Erler DV, Farzana T, van Zwieten L (2016) Delayed permanent water rice production systems do not improve the recovery of 15N-urea compared to continuously flooded systems. *European Journal of Agronomy* **81**, 46–51. doi:10.1016/j.eja.2016.08.009

Vlek PLG, Byrnes BH (1986) The efficacy and loss of fertilizer N in lowland rice. *Fertilizer Research* **9**, 131–147. doi:10.1007/BF01048699

Westcott MP, Brandon DM, Lindau CW, Patrick HW Jr. (1986) Effects of seeding method and time of fertilization on urea-nitrogen-15 recovery in rice. *Agronomy Journal* **78**, 474–478. doi:10.2134/agronj1986.00021962007800030016x

Williams RL, Angus JF (1994) Deep floodwater protects high nitrogen rice crops from low temperature damage. *Australian Journal of Experimental Agriculture* **34**, 927–932. doi:10.1071/EA9940927

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